Receiver Performance Tradeoffs

Overview

The design of portable radios requires that many additional design considerations be evaluated and appropriate tradeoffs made to keep portable performance high without sacrificing size, weight and battery life. The purpose of this paper is to define some of these tradeoffs in light of current design restrictions.

Shown in Figure 1 is a typical RF front-end architecture. It will be used as a reference model for further discussions. This discussion involves the premise that these changes are to improve future radio design, not to retrofit older designs.

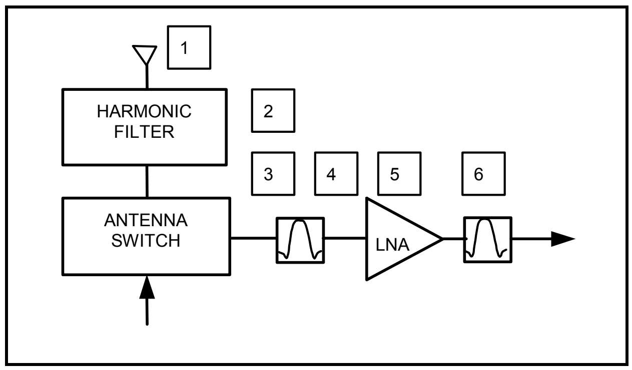

Figure 1

The individual components include:

1. The portable antenna
2. The harmonic filter requires passing of the current 800 MHz band as well as the 700 MHz band.
3. The Antenna Switch
4. The preselector filter (Bandpass)
5. A Low Noise amplifier with it's associated noise figure and IIP^3
6. Additional bandpass filtering prior to the receivers mixer and Intermediate frequency amplifier

These various components all have requirements that have to be satisfied based on user requirements.

1. The portable antenna must pass the required frequencies and be rugged and of a small size to make its utilization comfortable for the end user. The affects of the antenna are generally uniform across all the frequencies of interest. Some variations exist due to where the radio is carried and how it may suffer from increased losses due to body coupling and shielding.

2. The harmonic filter has to pass the desired transmit and receive frequencies. The filter has to have low insertion loss or transmit power would be dissipated as heat and battery power requirements would be increased.

3. The antenna switch is used to protect the sensitive receiver circuitry from the high power of the transmitter.

4. The preselector filter has to pass the receive bands. For the newer radios, this is quite complex, as the receiver bands are not contiguous. The 700 MHz public safety band is 764 - 776 MHz while the current 800 MHz band is 851 - 869 MHz. The currently proposed modifications to the 800 MHz band would reduce the current 18 MHz window, but the requirement for interoperability to other existing systems that have not or will not participate in the band reorganization requires the current bandwidths be passed. If and when all users have migrated to the proposed new 800 MHz band plan, then the bandwidth of the preselector could be reduced. Additional discussion on the preselector filters is provided later.

5. The low noise amplifier essentially determines the intermodulation performance of the receiver due to it's third order input intercept specification (IIP^3). The current state of the art limits receiver IIP^3 due to the requirement for increased current drain to achieve higher performance. Sensitivity is determined by the noise figure of the LNA and any losses that occur before it, although losses after are affected, but to a lesser degree.

6. The second filter is required to provide the proper match and additional attenuation to far out signals that can cause spurious receiver responses, such as the "image" spurious response.

Reduction of Interfering Signals

Filtering, attenuation or limiting can reduce interfering signals. Notch filtering reduces the amplitude of the interfering signal relative to the desired signal. Attenuation reduces all signals by the same amount, but can provide different results when intermodulation is involved. Limiters provide bounds for the magnitude of very strong signals while leaving weaker signals unaffected. Note that any component preceding the LNA increases losses and thus raises the system noise figure, thereby reducing sensitivity. Losses introduced typically range from 0.25-5.0 dB per circuit.

Notch Filters

Notch filtering reduces the amplitude of interfering signals by reflecting the undesired signal back toward the source. This effect is called return loss. Notch filters may be tunable or fixed, but fixed notches apply only where there is a well-known and unchanging source of interference. Since private land mobile radios are used with a wide range of band plans, fixed notch filters are impractical.

Tunable notch filters typically rely on voltage-tuned varactor diodes for changing the center frequency of the notch. Since a varactor is a tunable capacitance, multiple pole filters require multiple varactors, as well as the biasing and control circuitry to tune the filter. This also usually implies software for filter control, although analog or ASIC techniques are possible.

Notch tuning may be fixed or variable. Fixed tuning is generally simpler and cheaper and could relatively easily be incorporated into the manufacturing process. Variable tuning may be adaptive or non-adaptive. Non-adaptive may be incorporated into the radio's control process for factory tuning or by the end user for their selection based on local frequency band plans or interference scenarios. Adaptive control typically requires a complex algorithm and of it's' associated software. These factors make adaptive control unsuitable for low-tier radios without significant development effort and associated additional costs.

Notch Filter Advantages

Notch filter rejection is determined by the frequency separation between the desired and undesired signals. When there is a very large dynamic range between desired and undesired signals, the notch filter may be the only solution.

Notch Filter Disadvantages

Multi-pole filters can require significant space for the filter, bias and control circuitry, producing an increase in size and weight of a radio. Increased parts count produces higher unit production cost and potentially lower reliability. Achieving high P_{1dB} may require high bias on the varactor diodes that, along with bias and control circuit power requirements, may lead to significantly increased battery drain. Multi-pole filters may also introduce loss raising the receiver's noise figure and reducing its' sensitivity. Additional information on this effect is provided later in this document.

Attenuators

Attenuators decrease the power input to the LNA for all signals equally. They are useful if there is high power in both the desired signal and undesired signals and the basic requirement is to keep the LNA from generating intermodulation products. They raise the noise figure and reduce sensitivity, but with a strong desired signal these are less critical, as is typical in interference-limited systems. However in noise limited systems, the loss can make the desired signal unusable. In addition, when the undesired signal has a large amount of OOB (Out-Of-Band) energy that falls on the victim's channel, the suppression of both signals is the same. The OOBE (Out-Of-Band-Emissions) may limit the performance level of the desired signal or be strong enough to prevent achieving a usable C/(I+N) value.

Attenuators may be fixed or variable, but the usefulness of a fixed attenuator in front of an LNA is extremely limited. For example a fixed attenuator might improve intermodulation performance as a tradeoff of sensitivity. Variable attenuators may be implemented as switchable fixed pads.

Attenuator Advantages

Variable attenuators can be small, low power, low cost and use little board space. They may be easily controlled with hardware (analog, digital or ASIC) or software, depending on the functionality desired.

Attenuator Disadvantages

Any attenuation in front of the LNA reduces receiver sensitivity. Use of an attenuator in an edge of coverage area may render the desired signal too low to achieve the desired level of performance. There is some impact to size, weight and cost of the radio. Parts count increases, reducing reliability. Conventional radio systems employ considerable scanning to find other important calls. The impact of latency and hysteresis may limit their applicability. Channel scanning, Rayleigh fading, individual channel variations in trunked systems (i.e. one has an IM product while another does not) and handoff issues will require evaluations.

Limiters

Limiters limit the maximum signal strength input to the LNA through the use of back-to-back diodes. The limiting action produces harmonics which increase in amplitude with increasing limiting, i.e. the higher the amplitude of the input sine wave, the more it is clipped and converted into a square wave and the higher the harmonic content of the resulting output. Limiters may be fixed, with the limiting amplitude set by the reverse breakdown voltage of the diodes, or variable with the limiting amplitude set by a bias circuit.

Limiter Advantages

When an undesired signal is much larger than the desired signal, limiters can reduce the amplitude of the undesired signal with little attenuation of the desired signal. They are generally small, low cost and require little board space and little or no power. They generally have little affect on sensitivity.

Limiter Disadvantages

Limiters generate harmonics and the operational environment must be such that their use does not create new problems. Limiters add to parts count and thus reduce reliability. There may be some, though typically little, increase in power consumption, board space, size and weight.

High P_{1dB} and IIP^3 Devices

Typical LNA's have a P_{1dB} on the order of 10 to 15 dB below the IIP^3. Very strong signals can saturate the LNA and produces harmonics. The IIP^3 is a theoretical point used to calculate the level of intermodulation that would be produced by source signals of a known level. The higher the IIP^3, the better the intermodulation performance obtained. LNA's with high P_{1dB} and IIP^3 are available.

High P_{1dB} and IIP^3 Advantages

Using a higher P_{1dB} raises the threshold at which the LNA goes into saturation and increases the dynamic range of the RF front end. A higher IIP^3 reduces the level of intermodulation produced for a given level of source signal levels. Size, weight, parts count and board space may be unaffected.

High P_{1dB} LNA and IIP^3 Disadvantages

Higher P_{1dB} and IIP^3 are achieved at the cost of higher bias current to produce the higher output power required to achieve the same gain. This increases power consumption and heat, reducing reliability and increasing battery drain. Parts cost typically increases for higher power active devices. Higher LNA output requires the next component in line to have a higher specification as well, which can again raise power consumption, heat and cost.

Reducing Intermodulation After the LNA using Attenuation (Output Isolation)
A saturated LNA can generate harmonics and act as a mixer, thereby generating multiples of harmonics at its output. In-band mixing products pass through the output bandpass filter while out of band products are reflected back into the LNA by the filter. Once back in the LNA these intermods can again mix and further produce in-band interfering signals.

A technique for reducing the effect of unwanted out of band signals at the LNA output is to isolate the LNA from the filter through the use of a ferrite isolator or a pad (i.e. 6 dB) on the LNA's output. Ferrite isolators are low loss devices, but compared to a 6 dB pad they are large and expensive.

The output pad increases the return loss (decreases the VSWR) and in-band mixing products because the reflected signals in either case pass through the pad three times (output, reflection back and 2nd reflection) for an 18 dB reduction for out of band signals. The desired signal experiences only a single 6 dB reduction.

The use of a variable output pad is normally part of an automatic gain control (AGC) circuit.

Output Isolation Advantages
Output isolation reduces VSWR and in-band interfering signals caused by LNA saturation. Six dB pads are small, inexpensive and passive, requiring little additional board space, cost, size, weight or power. As passive devices they alter reliability very little. Receiver sensitivity is typically little affected by the addition of attenuation after the LNA.

Output Isolation Disadvantages
The gain/loss budget of the receiver must be modified, possibly increasing LNA gain to account for the output attenuator. This may raise power consumption somewhat, require a somewhat more expensive amplifier and have a small (normally negligible) effect on reliability and battery drain.

Fixed Filters

Mobile radios can be designed using fixed filters, as the size and weight penalties are insignificant compared to a portable. Bandwidths narrower than 40-50 MHz will require significantly greater insertion loss. Because of the two widely separated receiver bands, dual, or parallel, filters would be required for fixed filters. This potentially increases both size and weight making tunable filters more appealing.

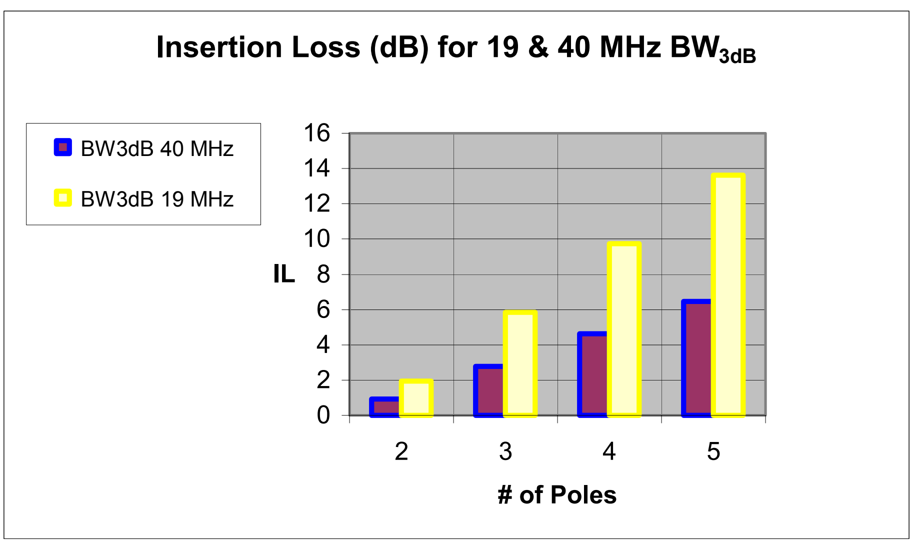

Figure 2 - Insertion Loss As A Function Of Bandwidth And Filter Sections

Tunable Filters

Changing the resonant frequency of a tuned circuit can be accomplished by varying either its inductance or capacitance. Because of their smaller size and higher Q, capacitors are generally chosen as the tuning element. One way to accomplish this is by allowing the capacitance to be a bank of switched discrete capacitors. Far from ideal, the PIN diode remains the preferred RF switching component.

Selecting a Tunable Filter

Selecting the optimal filter for the job requires evaluating numerous potential tradeoffs. These relate to technical performance, size/weight, and cost. On the technical side, the filter performance characteristics can be summarized:

- Insertion Loss
- Bandwidth/Selectivity
- RF Power Handling
- Intercept Point (IP^3)
- Image Spurious Rejection
- Tuning Range
- Tuning Speed
- Power Consumption
- Physical Size
- Weight

Insertion Loss and Bandwidth/Selectivity

A filter's insertion loss and bandwidth are inversely related: the narrower the bandwidth of a filter of a given technology, the higher its loss. The bandwidth-loss relationships are measured by a filter designer using the property called "unloaded Q". This property measures the Q of an unloaded resonant circuit. Q is mathematically defined for a resonant circuit by the equation:

$Q = \omega_o \bullet R \bullet C$, or $Q = \dfrac{R}{\omega_o \bullet L}$

By inspection, it can be seen that the higher the value of R, which for an unloaded resonator represents the lossy component, the higher the value for Q. The insertion loss of a 2-pole Butterworth filter is given by the equation:

Insertion Loss (dB) = $20 \bullet Log\left[\dfrac{Q}{Q - \sqrt{2}/BW_{3dB}}\right]$

This shows that the way to improve a filter's IL, for a given technology and bandwidth, is to increase the Q of its resonant circuits. Generally, this means larger size and/or increased DC power consumption, and higher cost, due to higher quality components.

RF Power Handling

This parameter can be the most important one in selecting a tunable filter. As opposed to fixed tuned filters, which consist of passive components, tunable filters contain active components that have limited linearity. The 1dB compression point of a filter is the RF signal level where IL increases by 1dB. For a tunable filter, this occurs when the RF signal's peak voltage imposed across an active tuning component, whether PIN diode or varactor, approaches the DC bias voltage applied. For PIN diodes, power handling can be improved with increased reverse bias, however care must be taken to ensure the sum of the bias voltage and the peak RF voltage do not exceed the breakdown voltage of the parts. Insufficient forward bias current can also limit power handling but is usually of secondary importance.

Intercept Point (IP^3)

Third order intercept point is a figure of merit for linearity and is closely related to the 1dB compression of the filter. When two large "interfering" signals (F1 and F2) are applied to a filter, two new signals are generated that appear on either side of the interferers and spaced from them by F1 - F2. If these interfering signals occur within the filter's passband, the distortion products can be large and easily fall right on top of a desired signal. In a tunable filter, this distortion is caused by the non-linearity of the active components when large RF voltages are imposed on them. Inband IP3 is generally 10 to 15dB higher than the 1dB compression level of a filter. The amplitude of the distortion products decreases as the interfering signals are moved out of the passband and on to the filter skirts. Note that even though the filter being specified may not have to handle high RF levels, the requirement for IP3 may drive it's size, weight, and cost due to the relationship between RF power handling and IP3.

Tuning Range

The narrower the tuning range required of the filter, the higher the performance. If the desired tuning range can be reduced, or two narrower filters can be utilized, usually at least one other technical parameter can be significantly improved.

Power Consumption

PIN diodes require DC power when forward biased. Generally, by increasing the forward bias of a diode, unloaded Q is increased and thus IL improved.

Battery Considerations

Portable radios are battery powered. Considerable discussion has highlighted that many parameters are heavily influenced by current drain. Increased current drain requires larger batteries, running counter to portable requirements. Private Land Mobile Radio systems have different operational requirements hence different battery requirements.

Public Safety and Industrial customers use their radios in severe weather environments. High energy density batteries typically have poor low temperature characteristics, making Nicad batteries the preferred source. This is different than commercial systems where radios are not subjected to the same requirements.

Batteries have to last for a normal shift at a predictable duty cycles of: Transmit, Receive and Standby.

High power is required due to the less number of sites. This increases current drain as well as the voltage level required.

Public Safety radios require rapid un-muting, less than 500 mS. As a result, battery saving techniques such as "sleep modes" are not applicable.

Dispatch modes of operation inherently create a higher level of receive traffic. Speaker volume levels are higher so current drain is higher.

Scanning to other conventional channels is frequently a system requirement, causing increased current drain.